

COMMUNICATING THROUGH THE USE OF VIBROTACTILE DISPLAYS FOR DISMOUNTED AND MOUNTED SOLDIERS

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ABSTRACT

The purpose of the studies reported here was to determine if participants wearing a purposed-designed tactile display could accurately report cue localization and messaging while undergoing different levels of physiological stress. Experiment 1 found that participants could effectively receive tactile messaging while navigating a physically challenging obstacle course. Experiment 2 demonstrated that tactile localization could be achieved by participants experiencing extreme whole body vibration produced by a vehicle simulator which replicated movement of different military vehicles in extreme conditions. Collective results illustrate that the current tactile display has significant potential for communication and/or directional cueing in demanding, real-world conditions.

INTRODUCTION

Combat conditions can impose significant demands on Soldier senses, limiting their ability to communicate through normal auditory and visual pathways. Noisy (e.g., weapon fire, vehicle engines) and murky (e.g., smoke, sandstorm) conditions can hinder the ability to communicate critical data, such as relevant threat information or simple squad movement instructions. In an environment replete with visual and auditory signals and noise, one way to circumvent this issue is to communicate through a relatively unused information channel: touch. Cutaneous communication systems have enjoyed considerable success in many domains, such as aircraft stick shakers, cellular telephone vibratory alerts, and reading using Braille. However, tactile displays are not as pervasive in military settings and may offer a relatively unexploited sensory channel for soldier communications. The goals of the present studies were to assess the performance of wearable tactile informational display systems in controlled field conditions for both dismounted and mounted operations and evaluate their relevance to systems like the Army Future Combat Systems and Future Force Warrior.

According to multiple resource theory (see Wickens, 1984, 2002), parsing information across the input modalities can alleviate sensory bottlenecks in conditions of high workload, and reduce interference across visual and auditory channels. Tactile displays

offer additional advantages. First, they are non-illuminating and acoustically covert, allowing the soldier maintain a stealth advantage. Conversely, traditional visual and auditory displays can mask important environmental information, such as distant enemy movement or approaching footsteps. Tactile displays also offer the advantages of self referent-presence and omnidirectionality.

Our research group, in partnership with industry, has designed a wearable tactile display capable of delivering patterns of vibratory stimulation at multiple loci. This system is able to convey information clearly beyond simple alerts or directional cueing. The display allows for precise control of frequency, gain, and onset times. With this level of stimulus control, consistent patterns can communicate complex messages, as well as simple alerts. Stimulus parameters have been derived, based upon feedback from a group of subject matter experts consisting of retired US Soldiers and Marines, to tactually convey key hand and arm signals. The reason for this was three-fold. First, hand and arm signal movements have a spatio-temporal patterns that can be conveyed via comparable patterns applied to the skin. These tactile signals could be presented covertly, without soldier movements that may signal their position to an enemy force. Second, the wireless transmission of these signals to the tactile display increases the likelihood that all squad members will receive a signal simultaneously. For example, when a team leader is informed of a potential threat and visually signals a "Halt" command, the soldiers in front of the team leader may not visually acquire the command while scanning their surroundings and maintaining local security. This can lead to an "accordion" effect, where by soldiers do not immediately respond to halt and become spread out. Third, Soldiers are already well trained on hand and arm signals. Therefore, it is reasonable to expect a degree of transfer of training to learn the tactful form, provided that the tactile patterns are designed intuitively to closely approximate their known visual counterparts. A tactile lexicon was developed using commonly used commands of the existing U.S. Army hand and arm signals (identified by the SME group; Department of the Army, 1987) allowing eye-free and ear-free communication between display wearers (see Gilson, Redden, & Elliott, in press). Concurrent with laboratory research, there was the need to determine if such a tactile displays could

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function in applied settings involving significant physical and cognitive demands.

The Mechanism of Display

For tactile displays that are based on vibration, the key skin receptors are the Pacinian corpuscles, which consist of nerve endings surrounded concentrically by layers of non-neural connective tissue. Pacinian corpuscles respond most readily to vibration at frequencies around 200-300 Hz, whereas, the free nerve endings are sensitive to much lower frequencies between 50-100 Hz (Bear, Connors, & Paradiso, 2001). Researchers have had problems when attempting to operationalize tactile displays since difficulties arise in the detection of the signal. For example, Sklar and Sarter (1999) experienced challenges with tactile signals being readily identified on the wrist and arm. Gilland and Schlegel (1994) reported that tactile communication applied to the head lowered performance on a concurrent task. These, and similar issues, present significant challenges to those seeking to use tactile displays in the real world.

As vibrotactile stimulator placement on the body has had the aforementioned difficulties on the head and extremities, the torso appears to be the preferred placement site for a wireless, fieldable system. The torso offers the least opportunity for tactors to shift during demanding physical tasks and also (based on SME input) would be the least likely location for it to interfere with combat tasks and for the stimuli to remain easily perceptible.

Our laboratory research has demonstrated that tactile cueing yields significantly faster and more accurate performance across varying lab test than comparable spatial auditory cues. Further research has demonstrated this finding is relatively stable across a variety of body orientations, even when spatial translation is required (Terrence, Brill, & Gilson, 2005) and under physiological stress (Merlo, Stafford, Gilson, & Hancock, 2006). The overall 99.4% accuracy rate displayed by the participants in the latter, physiological stress study was highly encouraging in respect to the potential of the current tactile display design. The accuracy of the messages and the reported intuitiveness with which they were received was also a testament to the potential utility of the present ‘language’ transformation format.

The natural progression for the present tactile system has moved beyond simple directional cueing and into the realm of more advanced covert communication. The purpose of the studies described here was to ensure that the tactile display can be useful in situations that are physiologically stressful and in a more applied setting than just running on a treadmill. Tactile signals that are only recognizable in pristine, quiet conditions may have limited use in real-world military operations. These studies show the results of the tactile systems as they

were tested in two separate operational experiments, one for dismounted and one for mounted soldiers.

Materials and Apparatus

The tactile system used in the present studies, the TACTile Information Communication System (TACTICS), was developed by researchers using a plunger-type vibrotactile actuator (hereafter referred to as a “tactor”), whereas much of the previously published research have used systems incorporating a ‘pancake type’ tactor, commonly used in cellular telephones. To determine if tactile communication and signaling would be viable under physiological stress, a durable field-worthy system was created using the plunger-type tactor due to its frequency and concentrated stimulus characteristics. The model C2 tactors, manufactured by Engineering Acoustics, Inc. (see Figure 1) are essentially acoustic transducers that displace 200-300 Hz sinusoidal vibrations onto the skin. This frequency range, in combination with their 17 gram mass, is sufficient to activate the skin’s Pacinian corpuscles. The C2’s contactor is 7 mm, with a 1 mm gap separating it from the tactor aluminum housing. The C2 is a tuned device, meaning it operates well only within a very restricted frequency range, in this case the optimal frequency of 250 Hz. These devices offer several benefits over pancake-motor type tactors that rely on a spinning arm to vibrate the entire tactor housing. First, the C2 tactor housing remains stationary as only the center plunger oscillates to provide a concentrated vibratory stimulus to a specific point on the skin. Second, pancake-motor tactors do not allow for independent control of frequency and amplitude. In order to raise the frequency to the range most readily perceived by the Pacinian corpuscle, the amplitude must also increase because the motor must spin faster and therefore increasingly displace the entire housing.



Figure 1. An enlargement of a single tactor, model C2, manufactured by Engineering Acoustics, Inc.

The number of tactors used on the different parts of the body should carefully be considered. Cholewiak, Brill, and Schwab (2004) found that for the torso, a ring of eight loci of vibration was the most efficient configuration with identification accuracy exceeding 90%.

The system uses a self-contained, wearable control box that provides power and signal generation for the tactors (see Figure 2). The control box houses a Bluetooth wireless communication device so that stimuli can be activated remotely from a Pocket PC or laptop computer.

The tactors themselves, as well as their associated wiring, are embedded in an elasticized belt worn around the torso slightly above navel height. The eight tactors in the system are spaced equidistantly around the abdomen with tactor 1 placed just above the navel and tactor 5 on the spine. The equidistant configuration is maintained due to the elasticity of the belt, allowing for ease of use from one user to the next without reconfiguring the display. Thus, there is a tactor every 45 degrees from the navel all the way around the body, (45 degrees x 8 tactors = 360 degrees).



Figure 2. Three tactile displays belt assemblies are shown above along with their Tactor Controller Boxes (TCB). Each box includes a wireless Bluetooth receiver and the controller circuitry and waveform generator.

The experiments presented here were conducted to assess the utility of complex tactile communication in both a mounted and dismounted environment. The first experiment assesses performance during individual movement techniques through an obstacle course. The second assessed performance in a vehicle simulator that was also providing whole body vibration consistent with military vehicle motion over selected terrains.

EXPERIMENT 1

Experimental Participants

For this experiment, twenty-nine male Soldiers from the Infantry Training Brigade (ITB) located at Fort Benning, Georgia participated in the assessment of the tactile messaging system on an obstacle course. The

mean age of the participants was 21 years and they were all in self-reported good physical health and they all could perform the assigned tasks of negotiating the obstacles.

Equipment

For the experiment, the tactile system presented four exemplar tactile patterns designed to be analogous to standard Army hand and arm signals (Pettitt, Redden, & Carstens, 2006). Tactile messages were created using the standard Army hand and arm signals (Department of the Army, 1987) as a design guideline. The four signals chosen for the experiment were "Halt", "Rally", "Move Out", and "NBC (nuclear, biological, chemical warning)." The tactile representations of these signals were designed in a collaborative effort between the present researchers and the aforementioned group of SMEs.

Experimental Procedure

Soldiers completed an obstacle course while receiving communication from either the tactile system or from a leader to their front or rear who provided visual hand and arm signals.

Soldiers were instructed to perform urban and non-urban tactical maneuvers and to conduct what is termed Individual Movement Techniques (IMT). The obstacles were categorized according to the activity the Soldier was performing at the time he was given a command. The four obstacle categorizations were patrolling, crawling, firing and climbing. Soldiers initially walked through the course, where each obstacle and position was explained before they began the first recorded trial. All Soldiers also completed one familiarization trial wearing their uniform, standard fighting load, tactile belt, and carrying their assigned weapon. The tactile signals that were used in practice were not the same as the signals used in the testing. The times and locations that the Soldier received the different signals were consistent among blocks. However, the individual Soldier never knew when or where they would receive either a hand or tactile signal.

Questionnaires were administered to elicit Soldiers' opinions about their performance and experiences while wearing the tactile system. The questionnaires were designed to enable Soldiers to rate the ease of receiving and understanding visual and tactile communications while negotiating obstacles, as well as their overall experience with the tactile system. Questionnaires were administered to each Soldier upon the completion of each experimental block on the course.

Each soldier was given approximately ten minutes of familiarization and training with the tactile system before beginning the obstacle course. Familiarization for every Soldier consisted of approximately 17 repetitions of the four tactile signals: three repetitions without wearing fighting loads, 4 times while wearing fighting loads, and 2 times each while wearing fighting loads in the kneeling, prone, combat roll, walk, and run positions/actions.

Soldiers were also presented with a refresher course on visual hand and arm signals. Soldiers were trained until they were 100 % accurate on all signals. Each Soldier was retested on all of the signals before each obstacle course experimental block. Upon completion of the training, the Soldiers were given a questionnaire designed to assess their perception of the training adequacy. Before the experimental trials were conducted, Soldiers participated in a practice trial on the obstacle course during which hand and arm signals and tactile signals were sent.

Soldiers completed three experimental blocks on the obstacle course. During each block, individual Soldiers wore the tactile system and were led through the obstacle course as if in a tactical scenario led by their team leader and followed by a squad leader. These positions are consistent with a Soldier acting as a member of a squad in a wedge formation. The team leader was designated to communicate visual hand and arm signals from the front and the squad leader from the rear. Tactile commands were communicated to the Soldier by a controller operating the control unit within blue tooth range of the squad member. A data collector recorded the time from the command's initiation until it was acknowledged by the Soldier and whether the correct response was given. As a visual distraction task, Soldiers were told to look for Special Forces, Airborne and Ranger tabs (military uniform insignia) that were placed at various locations on the course and to scan the woods for targets. At the completion of each block, a questionnaire was administered.

Results

Only a short period of time was required to train the Soldiers to become accurate on interpreting the tactile signals and for refresher training on the hand and arm signals. Soldiers became proficient after approximately ten minutes of individual training on the tactile signals and rated them as easier to learn than the hand and arm signals. All the Soldiers rated the training as being "good" to "extremely good".

Due to a floor effect in the time to respond to signals (the lowest possible time is 0.1 sec), the data are highly skewed. Analysis of variance (ANOVA) is based on the assumption that the data are approximately normally distributed. Thus all ANOVAs and follow-on comparisons reported here were completed using the log transformed data. However, when the log transformed data and the untransformed data were analyzed, the results were essentially identical. Table 1 shows the mean response times across the three IMT iterations for the three methods of signaling. For purposes of analysis, failures to respond to signals were coded as response times of 20 sec.

Table 1. Mean Response Times in seconds, Obstacle Course Trials

Signal Modality	Mean	SD
Hand signals -- rear	4.65	2.02
Hand signals -- front	2.93	1.17
Tactile signals	1.81	0.64

Table 2. Mean Log Response Times in seconds, Obstacle Course Trials

Signal Modality	Mean	SD
Hand signals -- rear	0.6325	0.1730
Hand signals -- front	0.4411	0.1429
Tactile signals	0.2393	0.1229

A repeated-measures ANOVA was performed on the log transformed scores (see Table 2). This analysis yielded a statistically significant effect for signal modality, $F(2, 58) = 80.3, p < .001, \eta_p^2 = .735$. Follow-up pairwise comparisons were done using Holm's Sequential Bonferroni correction to control for family-wise error (see Table 3). These follow-on comparisons show that response times were significantly faster with the tactile signals than with the hand signals, and that response times were significantly faster when the hand signals came from the Soldier's front rather than the rear.

Table 3. Follow-on Comparisons Mean Log Response Times, Obstacle Course Trials

Comparison	df	t	Obtained p	Required p
Rear vs. Front	29	5.92	<.001*	0.05
Rear vs. Tactile	29	12.03	<.001*	0.0167
Front vs. Tactile	29	7.25	<.001*	0.025

* $p < .05$, two-tailed

Soldiers rated both the "hand signals" and the "tactile signals" as each being very easy to learn. Soldiers rated both the "tactile commands" and the "front hand commands" as very easy to detect and interpret. One Soldier stated that the tactile system seemed to become progressively easier to interpret as the iterations progressed. By the third iteration, he stated that the tactile belt was easier and quicker to understand than clearly visible hand and arm signals. The "rear hand signals" were rated as being more difficult to detect and interpret.

An additional analysis on missed responses was conducted to categorize them into "failures to detect" the commands versus "incorrect responses" to detected commands. A Chi Square analysis was conducted on this data and showed there was a significant difference in the number of "failures to detect" among the three signal

modalities: $\chi^2(2, N = 30) = 18.5, p < .01$. There was also a significant difference in the number of “failures to detect” among the four obstacle types: $\chi^2(3, N = 30) = 7.82, p < .05$. The greatest number of “failures to detect” came with the “hand signals from the rear” and on the “climbing obstacles”. There was a non-significant trend for the greatest number of incorrect responses occurring with the “hand signals from the rear” and “on the climbing obstacles”.

Discussion

The tactile signal patterns were found to be intuitive and easy for the Soldiers to understand. Very little training time (less than 10 minutes) was required for Soldiers to become accurate on interpreting the four tactile signals used during the experiment. Results demonstrated Soldiers performing an obstacle course were able to receive, interpret and accurately respond to the tactile commands faster than when the information was passed by a leader in the front of a wedge formation or by a leader in the back of a wedge formation using conventional hand-and-arm signals. Soldiers also commented they were better able to focus more attention on negotiating obstacles and on local area SA when receiving tactile signals than when maintaining visual contact with their leaders in order to receive standard hand and arm signals.

There is reason to expect that tactile signals would be even more effective in more realistic operational context. The obstacle course made it much easier to see the hand and arm signals than it would have been if the experiment had been conducted for example in a wooded environment where vegetation and terrain features would have masked the leaders. The obstacle course made conditions identical for each run and therefore more amenable to anticipation thought consistency. Also the experiment was conducted only during daylight conditions which again made it easier to see the hand and arm signals than it would have been if the experiment had been conducted at night.. Soldiers indicated the tactile system allowed them to focus more attention on negotiating obstacles, and that it would be useful in tactical situations in which they would need to focus on other tasks such as security. Soldiers commented that it was very difficult to receive a visual hand and arm signal at certain points on the course where their full attention was given to negotiating the obstacle, or when they could not maintain visual contact with the leaders. Soldiers stated they knew immediately when they received a tactile signal no matter what obstacle they were negotiating.

The use of a tactile communication system has the potential to improve infantry team performance beyond that which is documented here. During this experiment leaders in the front and rear of the Soldiers were not obscured by terrain, vegetation or darkness. In other words, the conditions of this experiment were optimal for the Soldiers’ abilities to see the conventional hand and

arm signals. During combat situations, larger dispersions and obscurants could greatly inhibit reception of visual hand and arm signals. Visual barriers in an urban combat situation could impair hand and arm signaling. Also, hand and arm signals are traditionally passed along throughout the squad so that the time that the first squad member receives the signal could be much quicker than the time that the signal is passed to and received by the last squad member.

A tactile communication system allows simultaneous reception of signals by all squad members. For example, a “halt” signal sent by visual signals could result in a wave effect so that the last squad member to receive the signal could still be moving long well the time when the squad needed to stop. A “halt” signal sent by a tactile system can be received by all squad members in less than two seconds. A further benefit provided by a tactile system is the increased local situational awareness (SA) experienced by the squad because the tactile system would free their eyes from having to watch for visual signals (Smith & Hancock, 1995). A third benefit of adding a tactile system is that Soldiers would have two means of receiving communication because the visual hand and arm signals would still be available.

EXPERIMENT 2

The objective of this experiment was to determine how vehicle vibration affects detection and localization of vibrotactile signals.

Experimental Participants

Twelve individuals from the pool of civilian personnel at Aberdeen Proving Ground (APG) voluntarily participated in this study. There were 9 males and 3 females with ages ranging from 24 to 54 years. The average age was 37.7.

Equipment

A six-degree-of-freedom Ride Motion Simulator (RMS) was used to simulate movement of a High Mobility Multipurpose Wheeled Vehicle (HMMWV) and a Bradley Fighting Vehicle (BFV) moving over gravel and cross country terrain at an average speed of 20 mph (see Figure 3). Tactile signals were sent via the aforementioned tactile display. The C2 tactor was driven at two signal strengths. In the first condition, identified as TACTICS 1, the tacter signal frequency was set to the standard 250 Hz and at the optimal intensity used in previous experimentation. In the second condition, identified as TACTICS 2, the signal strength was analogous to the characteristics of a “pancake motor” tacter that vibrates at around 60 Hz. Stimulus matching was conducted in the laboratory until appropriate gain

settings subjectively matched the gain of the C2 operating at 250 Hz to the subjective operating intensity of the “pancake” motor-type tactor. Each signal consisted of one tactor vibrating for 0.5 seconds. The two conditions allowed not only for exploration in the effects of vehicular movement on tactile displays but also a comparison of two different tactile presentations, in this case a subjectively matched low frequency tactor to the tactile display used in the aforementioned studies.



Figure 3. A six-degree-of-freedom Ride Motion Simulator (RMS) was used to simulate movement of a High Mobility Multipurpose Wheeled Vehicle (HMMWV) and a Bradley Fighting Vehicle (BFV) moving over gravel and cross country terrain at an average speed of 20 mph.

Experimental Procedure

Each participant wore the tactile display around the abdomen, situated just above the navel. The experimental conditions were counterbalanced and subjective data about the systems were collected at the end of the experiment. The primary task of the participants was to detect and verbally state the spatial location of the tactile stimuli. Participants completed two training sessions, one with each tactile system. For each training session, 16 tactile signals were presented and participants verbally indicated the location of the vibration they received using the eight locations of the tactors in accordance with compass directions. Upon completion of the training, each participant was seated on the ride motion simulator and completed a practice trial to become familiar with how the simulator operated. Participants also received tactile signals at different locations around their waist to become familiar with how these signals felt. Again, participants verbally indicated the location of each signal.

For the experiment, participants were seated on the stationary RMS and baseline measures for each tactile system were taken. For the baseline, participants sat on the stationary RMS and received 16 tactile signals (two at each of the eight compass points), verbally indicating the location of the vibration they received (northwest, south, etc.). After the baseline measures were completed, participants were assigned a treatment condition and began the ride portion of the experiment. During the simulated ride, the tactile system generated signals at irregular intervals. Participants verbally indicated the location of the vibration, and no verbal report was coded as failure to perceive the stimulus. Response time was measured and each treatment condition lasted for approximately 3 minutes. Participants received a total of 16 tactile signals, two at each of the eight locations. Interstimulus intervals were randomized to reduce participant anticipation of the signals.

Results

Data were analyzed according to the percentage of detected signals, the percentage of correctly localized signals, and response time. In the baseline, participants were able to detect 100% of the tactile signals. Response time was equivalent for both systems. For the moving trials, 98.4% of the TACTICS 1 signals were detected and 93.8% of the TACTICS 2 signals were detected. Of those signals detected, 97% of the signals were correctly localized for both systems. Response time for both systems was 1.6 seconds. With respect to errors, the majority were localizations that were off by 45 degrees. Of the eight locations on the display, “West”, was the most frequently missed. It was originally hypothesized that “South” would be the most frequently missed due to its location over the indentation in the lower back, however, the data did not support this contention.

DISCUSSION

Clearly, tactile signals are registered and useful, even during high physiological stress and significant arousal situations. In contrast to some other prototype systems, the present one does not use the pager or “pancake like” motors that have been used in past research. The piston type tactor design and our present placement strategy appear to be very effective in maximizing signal reception. The potential for such tactile communications and the use of tactile displays for enhancing soldier performance seems particularly opportune at the present time. It has also not escaped notice that this system has a great potential for use by other military services and personnel in the civilian sector who also seek to increase communication capacity and alleviate visual and auditory overload in demanding operational environments.

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